Heavy Ion Driven Inertial Fusion Energy R&D Opportunities

1. Approach to test high current beam transport @ 5 Hz
2. Workshop: Accelerators for HIF-plans and status

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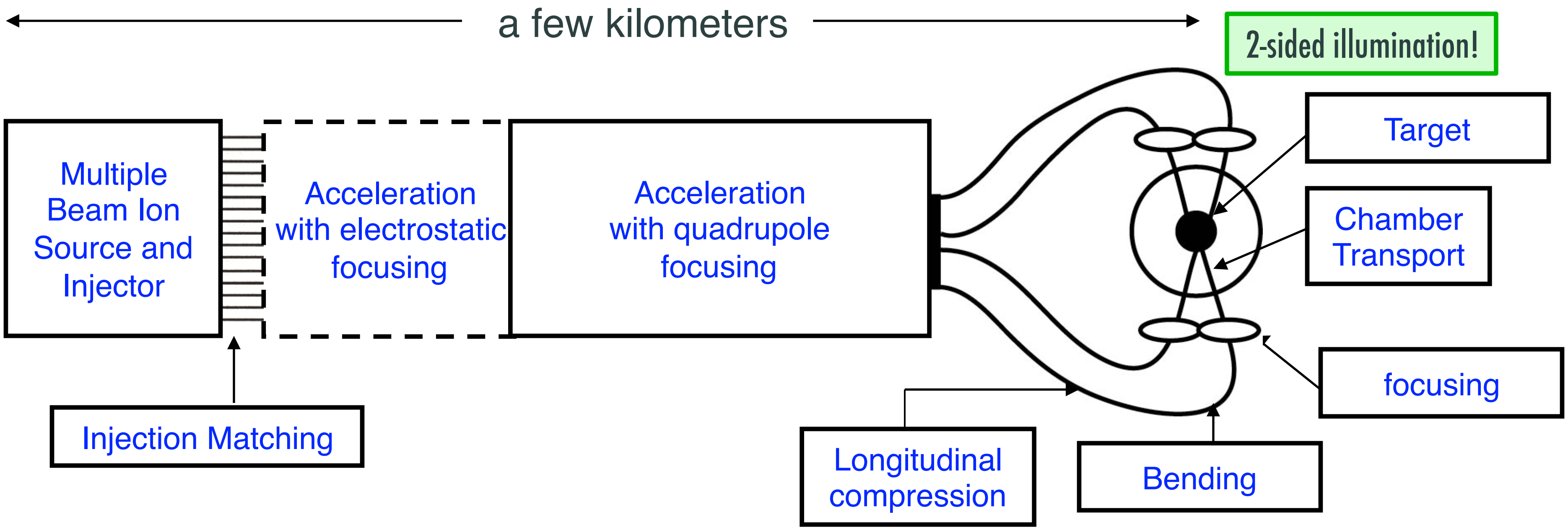
for the for the Heavy-Ion Fusion Science Virtual National Laboratory (HIFS-VNL)

Presented to the the 10th HIFS-VNL-PAC

LLNL, December 8, 2010

The Whole Accelerator:
An Induction Linac "Driver"



≈2-3 MeV
~1 A/beam
~ 20 μs
A ≥ 133
q = 1 *

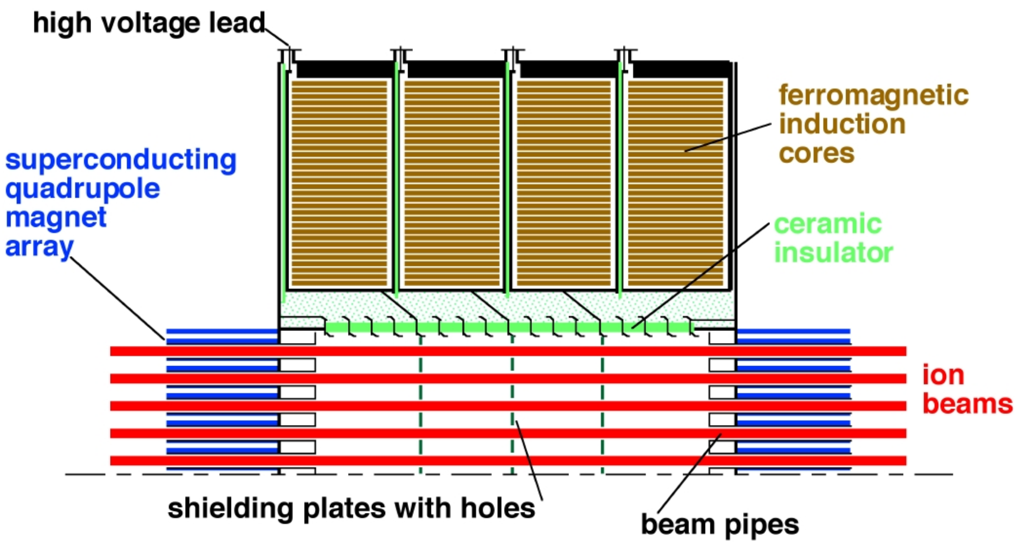
≈ 3-10 GeV
I ~ 200 A/beam
~ 200 ns

~3-10 GeV
~4000 A/beam
~10 ns

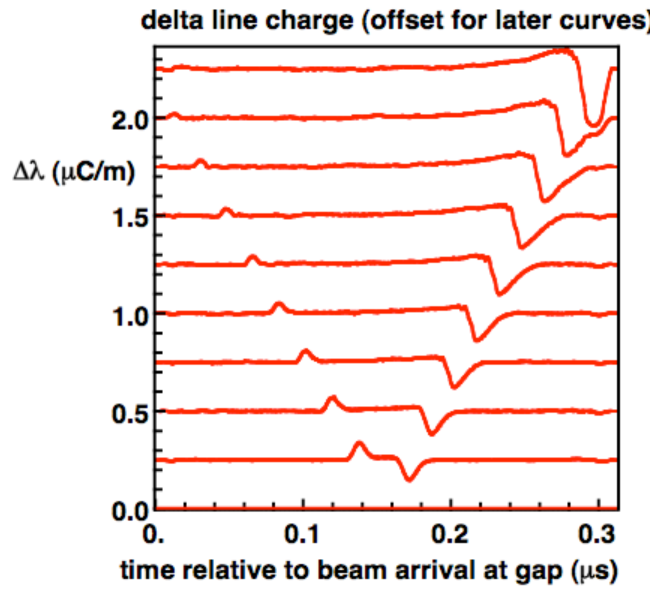
Power amplification to the required 10^{14} to 10^{15} W is achieved by acceleration and longitudinal bunching.

** q > 1 ? Difficult to get desired brightness, current.*

Multiple beams within single induction core



Growing & decaying space-charge waves

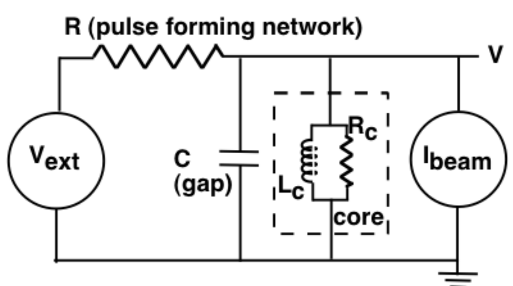


Premium on compact transverse focusing magnets

$$V = \frac{\Delta B \cdot area}{\tau}$$

$$area \propto (r_o - r_i)$$

$$mass \propto (r_o^2 - r_i^2)$$



(interaction of the beam with core impedance may cause space charge waves and emittance growth)

space charge wave transit times in a driver? 2-3, at most.

~1 synchrotron (single particle) oscillations

Superconducting array magnets share flux with neighboring cells.

Enhances field ≈30%, or more, depending on cell size.

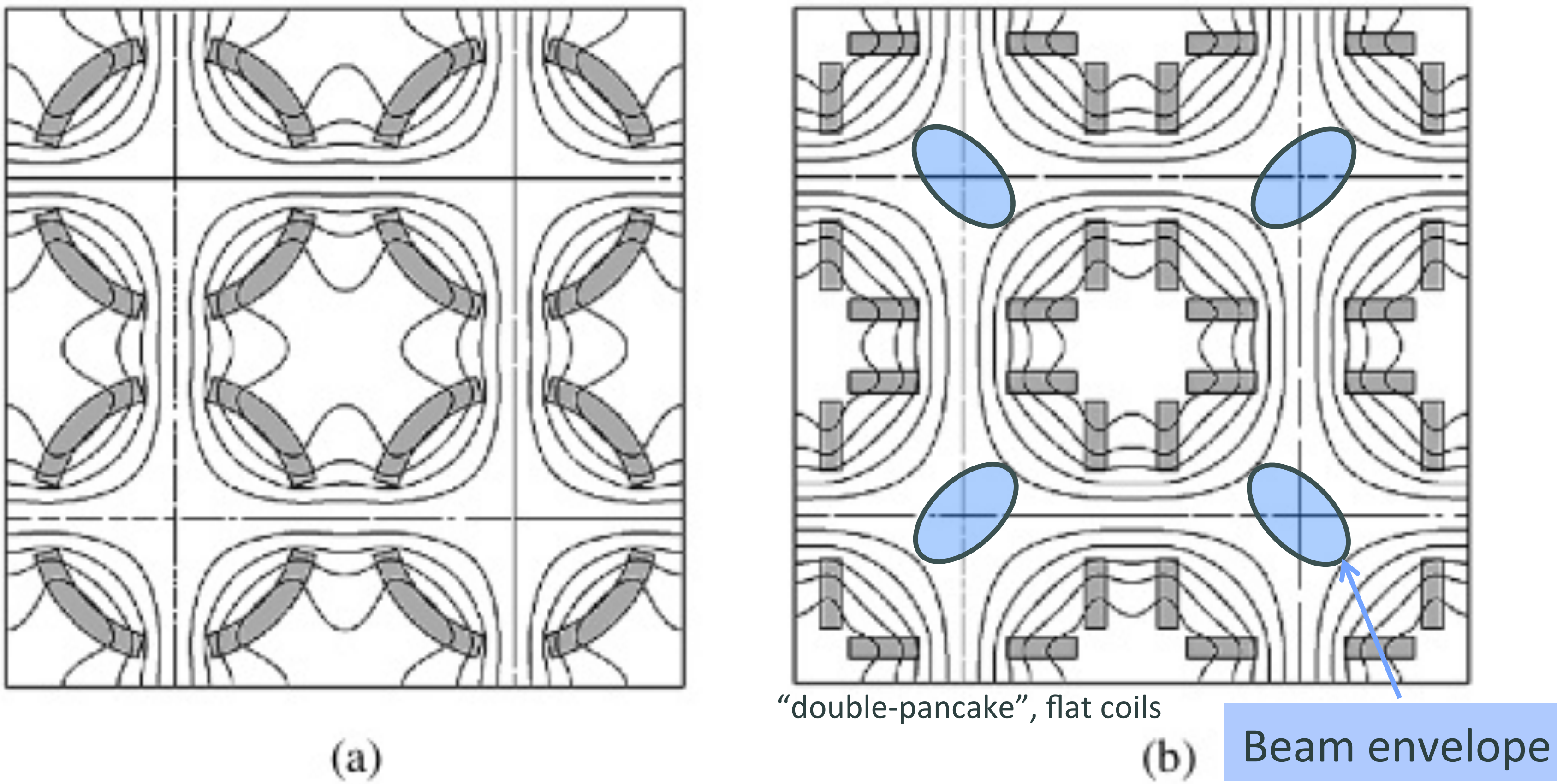


Fig. 2. Array configurations using (a) shell or (b) block coils.

At array periphery, every channel can be made the same with edge termination coils

4. Research Agenda: How to advance the accelerator science and target physics needed for heavy ion fusion?

If the scope of the VNL research program increases in part due to ignition in NIF motivating IFE, and the National Academy Review of IFE endorses a return to IFE research…

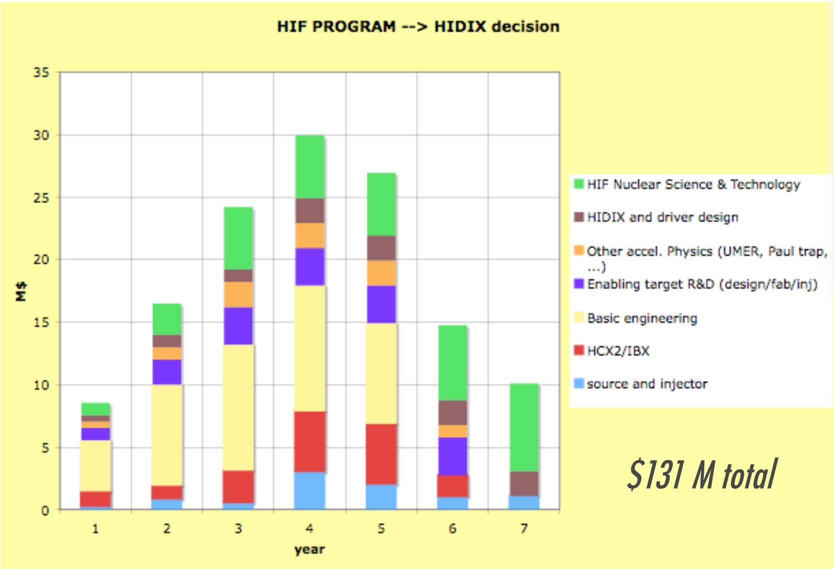
A balanced effort is required in:

A. *Target physics and design,*

B. *Accelerator physics and driver design,*

C. *Reactor and driver interface,*

D. *Technology development.*



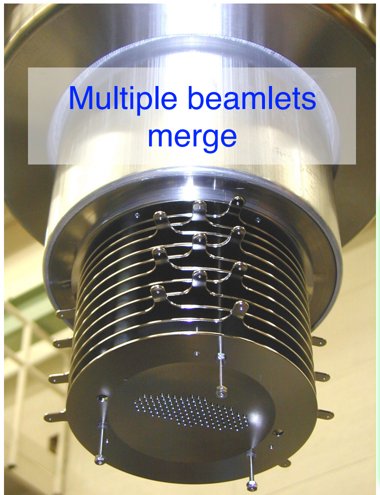
<u>*Guided by:*</u> At least one fusion energy driver design, and an intermediate beam and target physics test facility (T_{target}~100 eV) which also tests, in an integrated way, all the key beam manipulations of an energy producing driver (ETF).

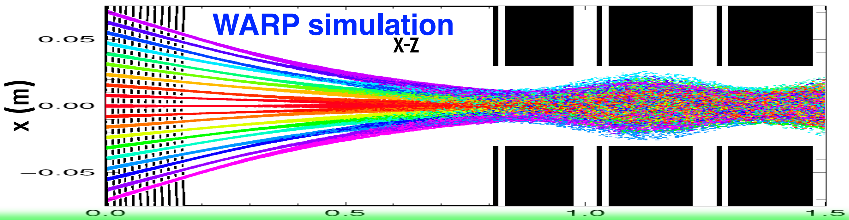
This is an aggressive research agenda with a very optimistic funding outlook.

Driver-scale beam experiments: Sources, injection, matching, transport. Must preserve brightness in the presence of high space charge … at ≈ 5 pps

Beam potential large ($\frac{\lambda}{2\pi\varepsilon_o} \approx 3$ kV). Beam especially susceptible to beam-gas, e-cloud

(a) High current, low emittance, surface ionization sources and **multi-aperture gas sources**

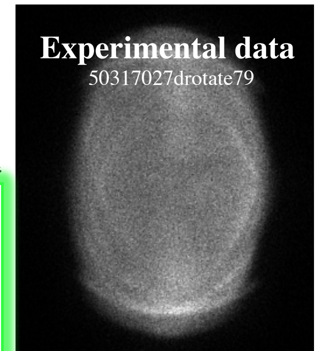




Remaining issues: Compact **arrays & gas load, matching, reliability, lifetime.**

Neg. ions? Higher charge states?

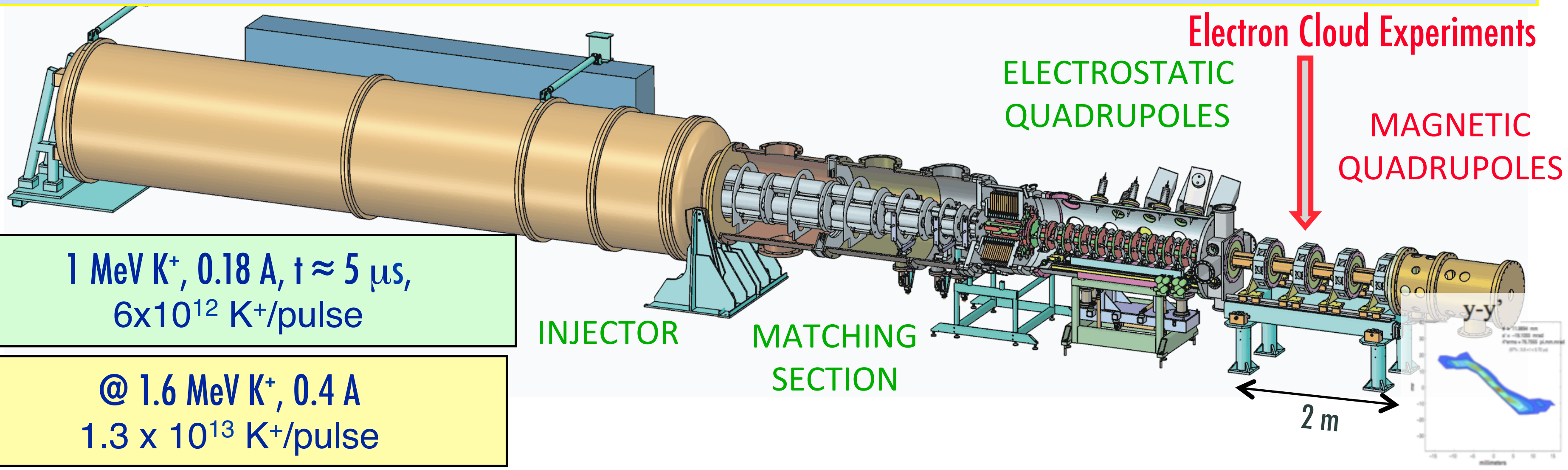
Study at 5 Hz (driver repetition rate)



Energy	Current
0.4 MeV	71 mA
1.6 MeV	568 mA

$\varepsilon_n < 1$ mm•mrad

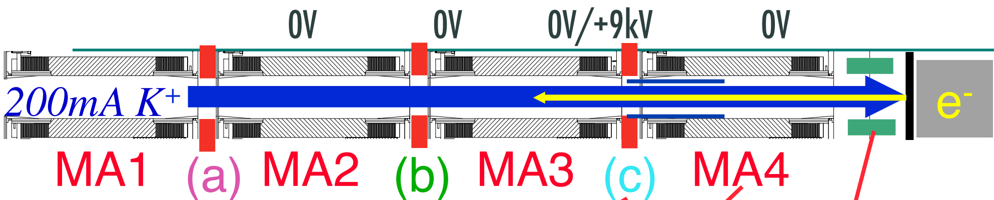
(b) **Injection, matching, transport** (HCX): explore & control e-cloud, halo-induced gas build-up



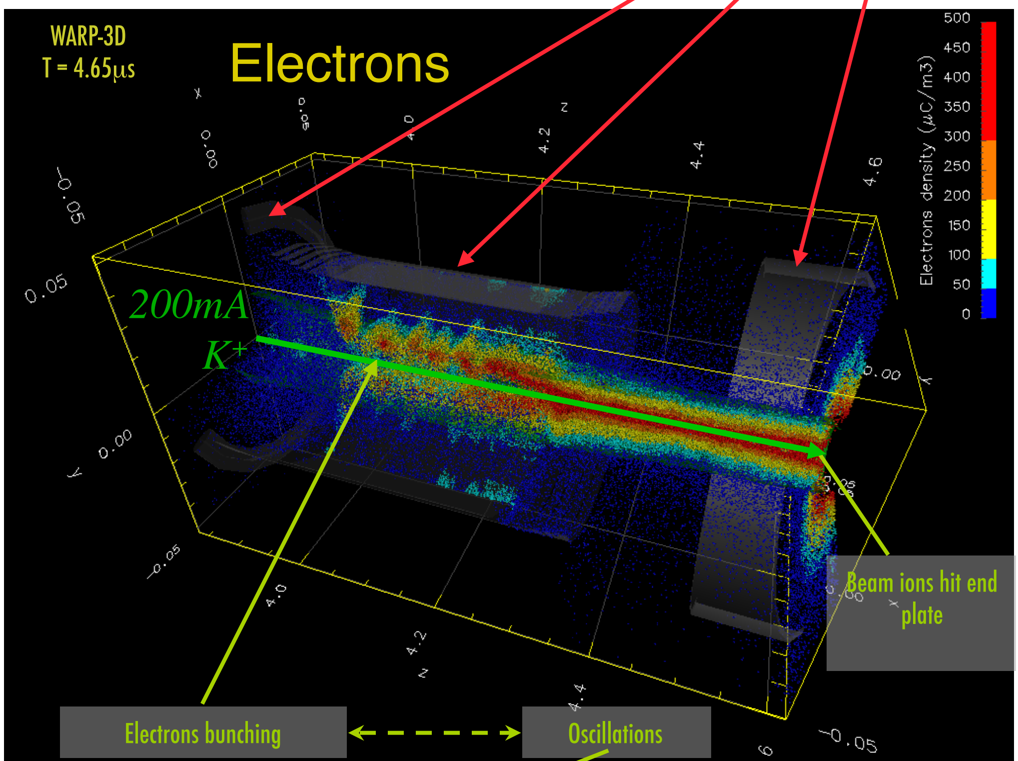
1 MeV K^+, 0.18 A, t ≈ 5 μs,
6x10^{12} K^+/pulse

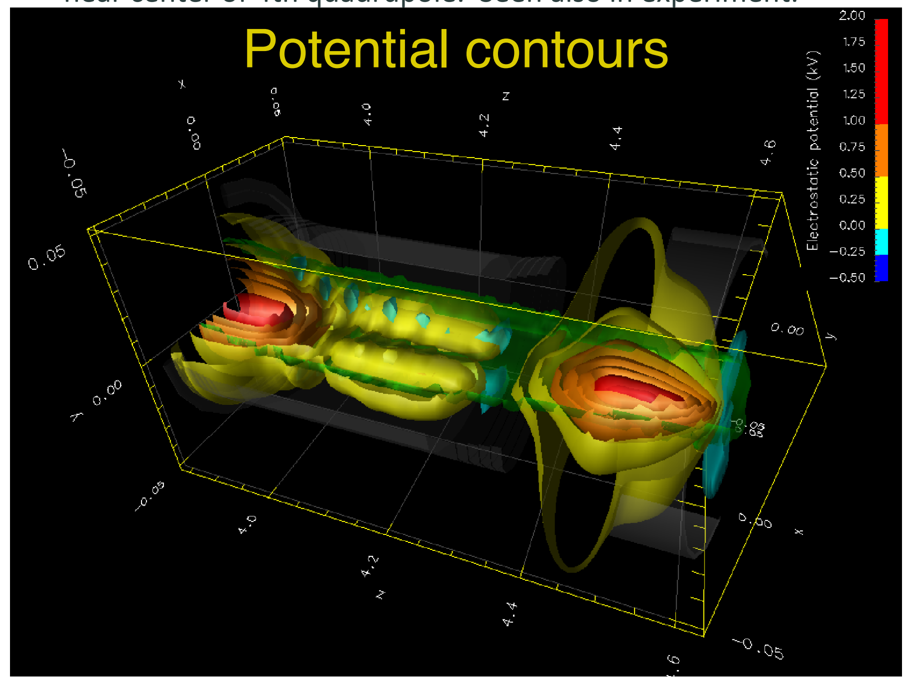
@ 1.6 MeV K^+, 0.4 A
1.3 x 10^{13} K^+/pulse

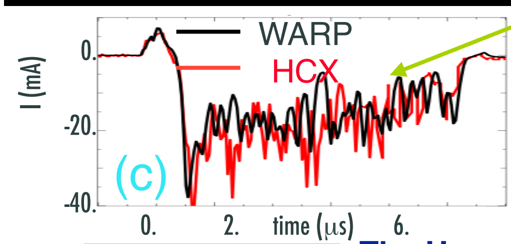
Importance of controlling, removing e⁻ from beam: Excess e⁻ can oscillate, interact with the ion beam.



Simulation discovered oscillation (λ~5 cm) growing from near center of 4th quadrupole. Seen also in experiment.

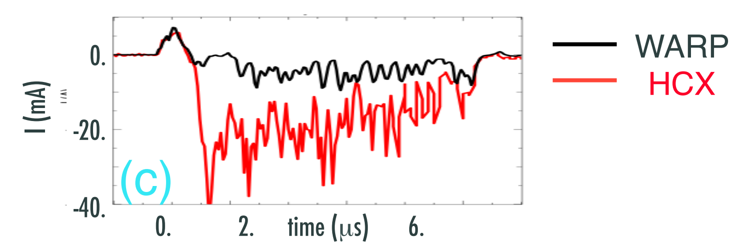






~6 MHz signal in (C) in simulation AND experiment

1. Good test of secondary module - no secondary electrons:



Most accelerators operate at a repetition rate exceeding HIF requirements, but at much lower current.

Experiments at 5 Hz are needed to explore gas buildup, beam-gas collisions, electron clouds, and to develop techniques to maintain low emittance.

With modifications,

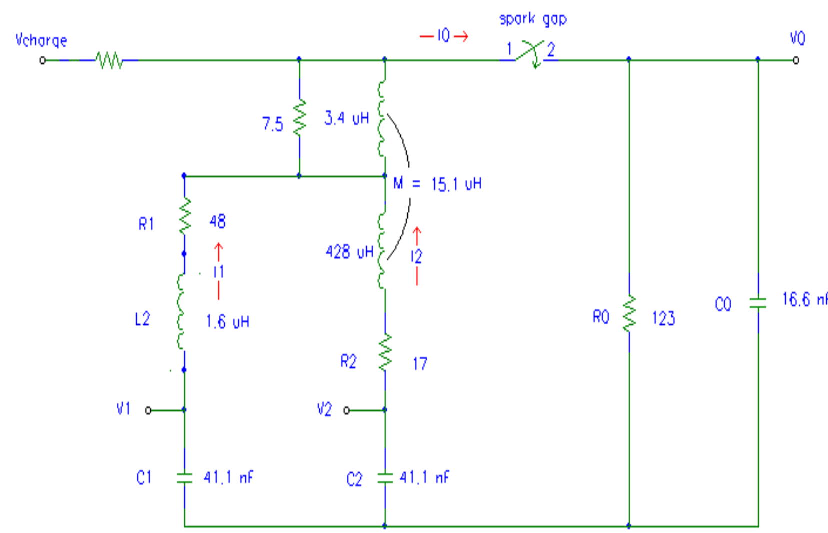
HCX is capable of doing such experiments.

Modification of HCX injector for 5 Hz operation

Acquire two charging power supplies; eg Glassman 8 kW, 270 mA peak.

(PS/SH030P270: $17.25k)

Reduce $R_{charging}$ → x Ω



Charging path resistors are low enough, heating is acceptable, the power supply is adequately protected.

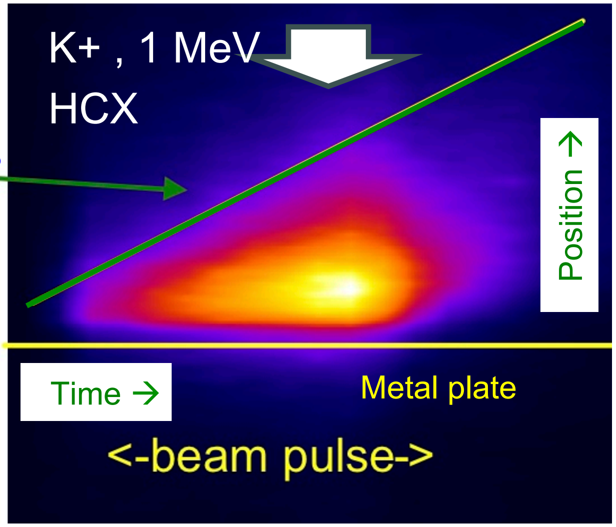
There are gas buildup issues to study and solve at short and long timescale.

SHORT – halo

Induced desorption

→ gas clouds moves toward beam

$v_{cloud} \approx 1.5$ mm/μs,
mostly H_2



$10^3 – 10^4$ neutrals / grazing incidence angle.

Mitigation strategies:
wall material choice,
beam edge ($2 \cdot r_{rms}$) to wall clearance
cold / warm bore

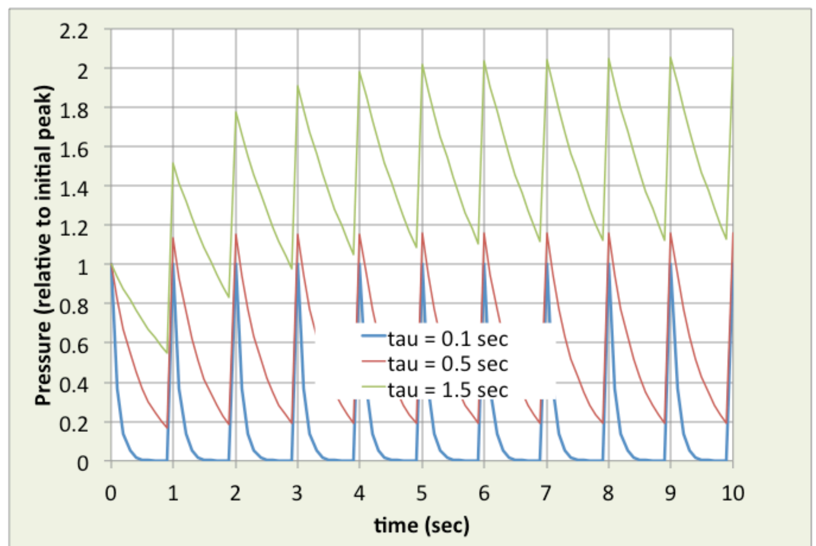
LONG

HIF driver: 10 Hz, $\mathcal{E}_f$ = 6 MJ, E_f = 6 GeV,
Q = 1 mC

E_i = 2 MeV, t_i = 20 μs
→ **duty factor, DF =2 x 10^{-4}**

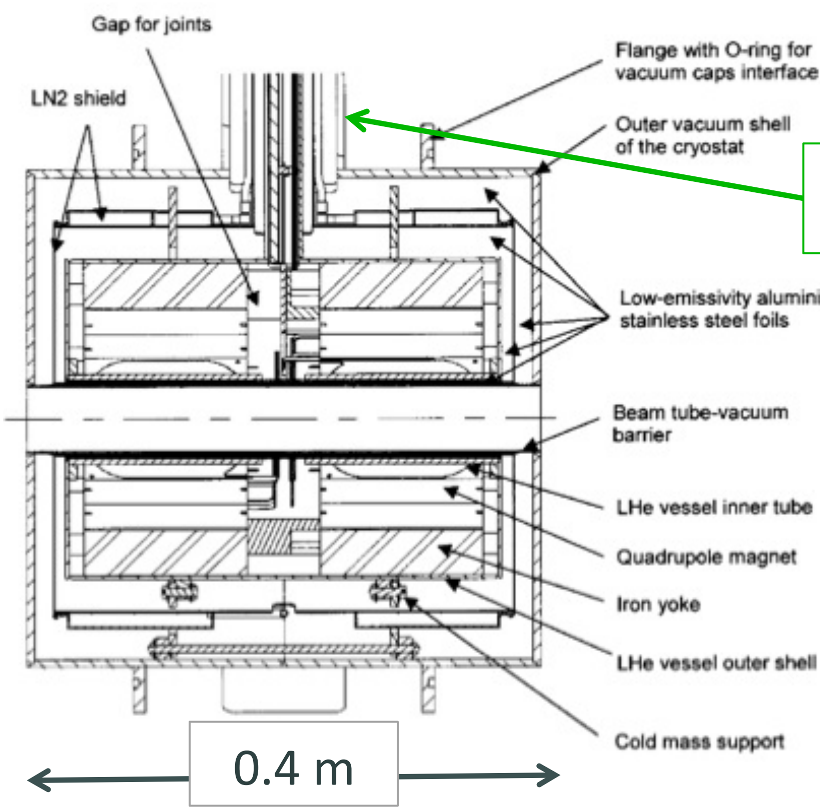
I_i = 1 mC / 20 μs = 50 A,
average current **$<I_i>$ = 10 mA**

(cf. ADS proton accelerators, ~10 MW, 1 GeV)



Superconducting magnet development

Prototypes reached 100% I_{ss} after a few quenches.
Flat coils, warm bore (59 mm ϕ)

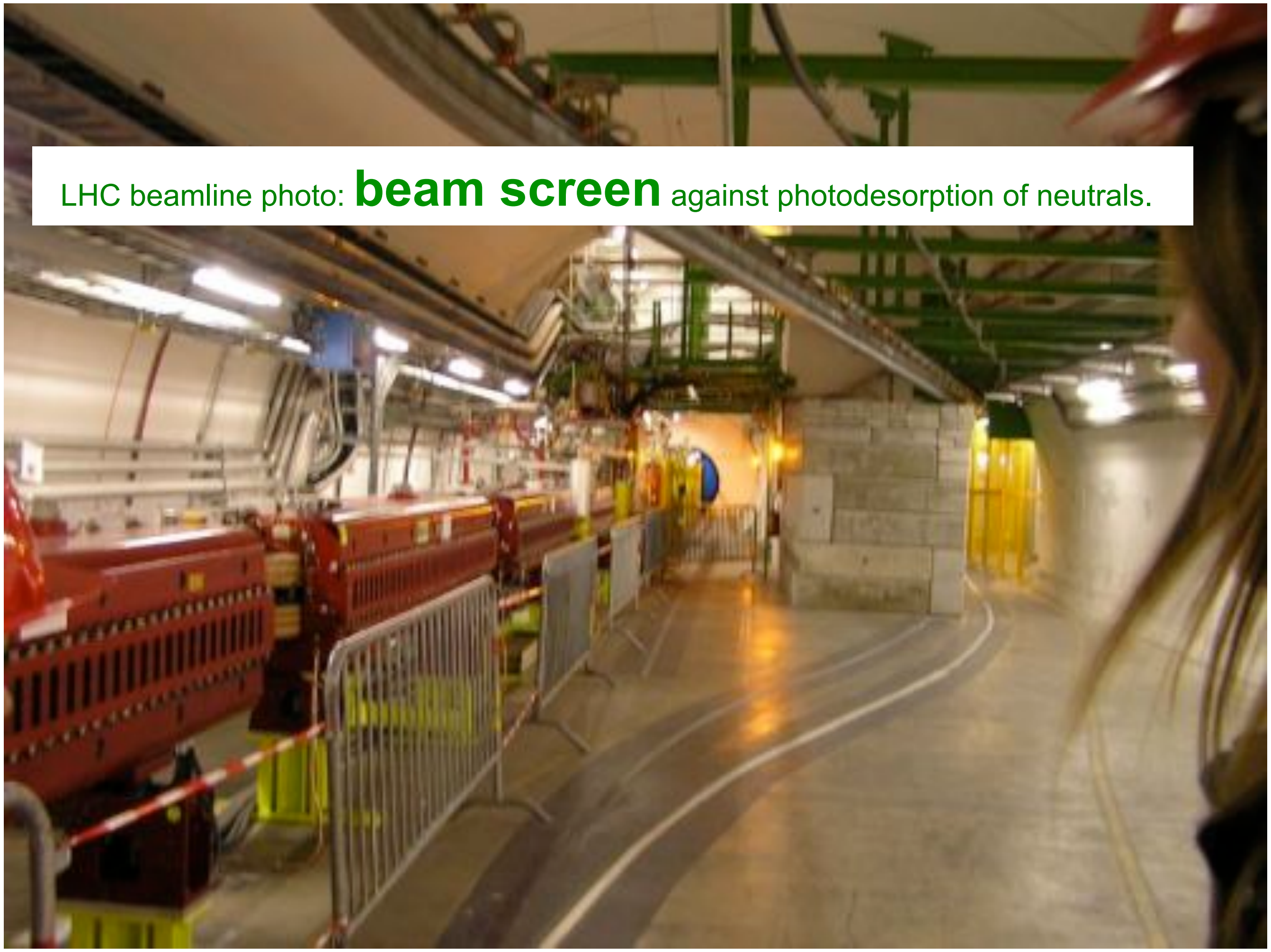


Long, narrow chimney for high current leads

Quadrupole doublet in Cryostat

$G(I_{ss})$ = 132 T/m. I_{op} = 0.85I_{ss}
L_{eff} = 104.5 mm. suitable for 2 MeV beam.
Field error: <0.5% at R= 25 mm (integrated)

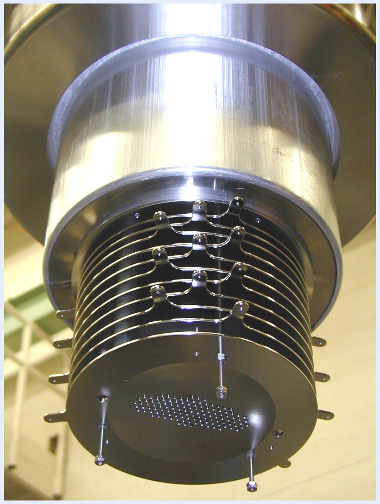
A cold bore would help with pumping. Issues are halo induced desorption.



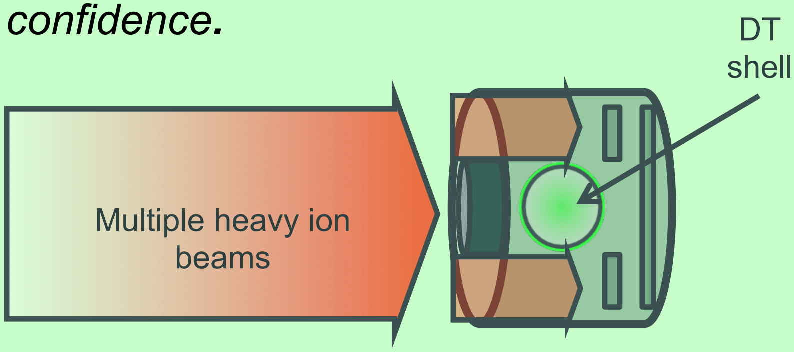
A beam screen *might* increase the unit cell size of a multi-beam array and impact the economics.

Significant progress is possible in the near term at a support level < $5M/year

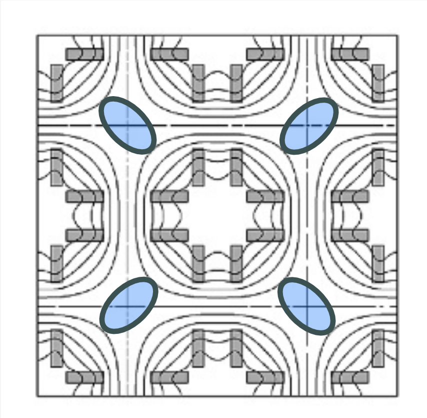
High intensity ion source, injectors: *10^{13} ions/pulse demonstrated. Toward 10^{15} - 10^{16} ions/pulse: multiple-beams,* ***rep rated. High space charge, gas load.***



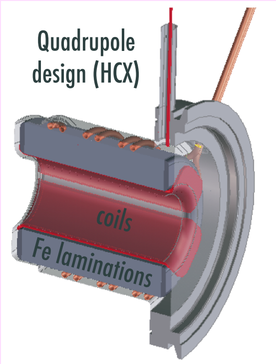
Target physics: *one-sided, indirect/direct drive, higher gain, simpler ion-beam, symmetry requirements would expand driver options and increase confidence.*

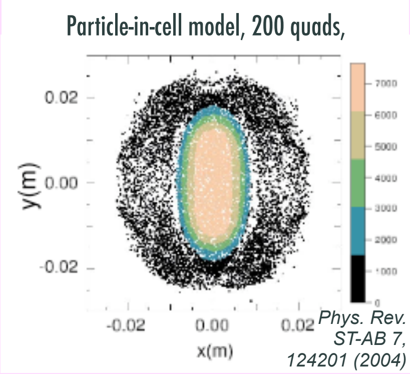


Basic engineering: *insulators, cores, pulsers, superconducting magnet arrays.*



E- clouds*: experiments, modeling to control e- from ion impact on surfaces, gas.*





Phys. Rev. ST-AB 7, 124201 (2004)

2. Workshop: Accelerators for HIF-plans and status

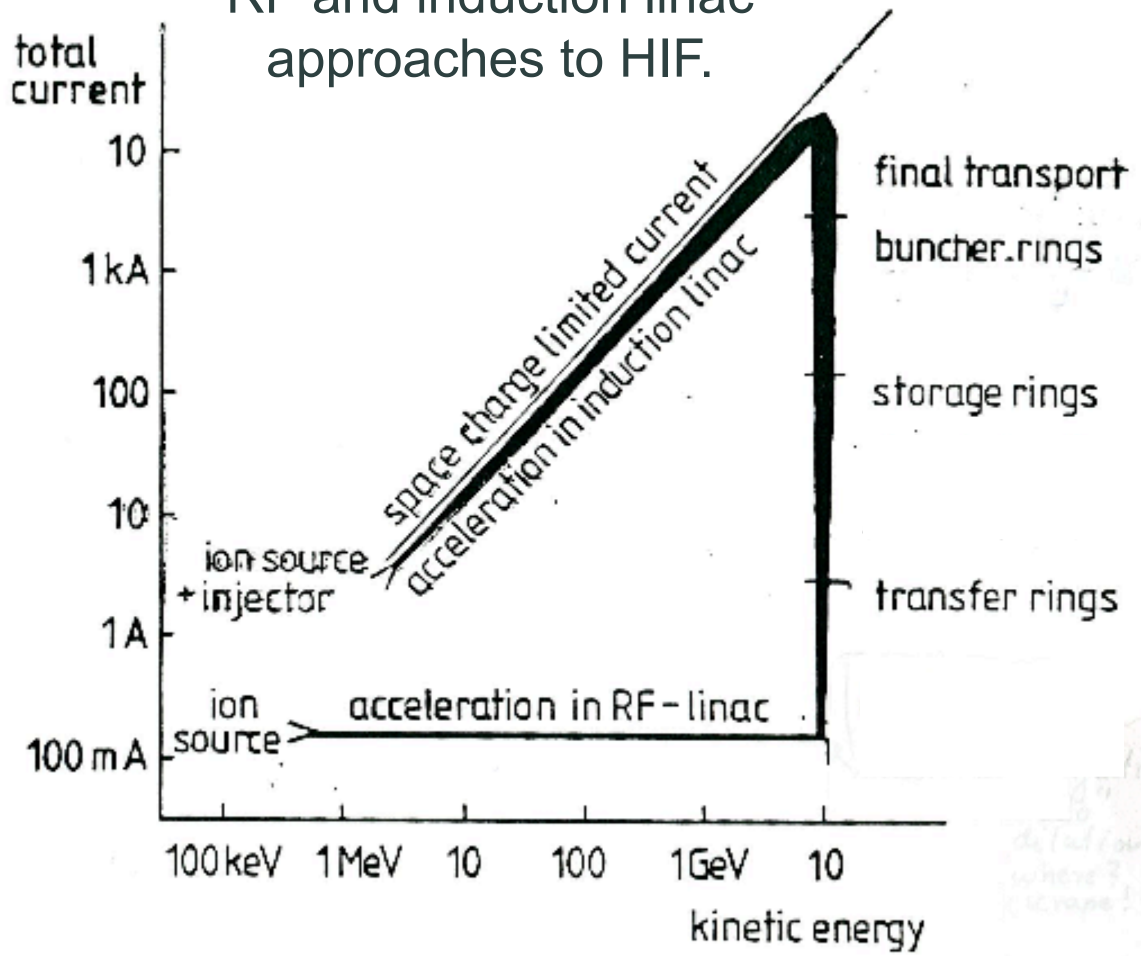
The advantages of heavy ion fusion (HIF), identified in many past reviews, still apply now:

1. **Accelerators** with **total beam energy** of ≥ 1 MJ have separately exhibited **intrinsic efficiencies**, **pulse repetition rates** (>100 Hz), **power levels** (TW), and **durability** required for IFE.
2. **Thick-liquid protected target chambers are designed to have 30-year plant lifetimes.** These designs are compatible with indirect-drive target illumination geometries, which will be tested in NIF experiments. **Thick-liquid protection** with molten salt having high thermal and radiation stability (LiF-BeF_2, or flibe) has been a **standard aspect of most HIF power plant concepts**.
3. Focusing magnets for ion beams **avoid most of the direct line-of-sight damage from target debris, neutron and γ radiation**. Thus, only the final focusing magnet coils need to be hardened or shielded from the neutrons.
4. Power plant studies have shown attractive economics and environmental characteristics (only **class-C low level waste**). Accelerator design efforts have converged on **multiple heavy ion beams** accelerated by **induction acceleration**. After acceleration to the final ion kinetic energy, the beams, which are non-relativistic, are compressed axially to the 4-30 ns duration, (few-hundred TW peak power) required by the target design. Simultaneously they are focused to a few millimeter spot on the fusion target.

Good progress until funding decreased steeply in ~2004.

Efficiency & ability to accelerate very high current are advantages of induction linacs.

RF and induction linac approaches to HIF.



In the early HIF workshops, significant participation from

LBNL,

LLNL,

LANL,

FNAL,

ANL,

BNL,

CERN,

GSI,

Rutherford,

SLAC.

Upcoming National Academy Review of IFE
(schedule not yet set)

"Statement of Task—Prospects for Inertial Confinement Fusion Energy Systems
A committee will be convened to assess the prospects for inertial confinement fusion energy systems. The Committee will prepare a report that will:

- Assess the prospects for generating power using inertial confinement fusion;
- Identify scientific and engineering challenges, cost targets, and R&D objectives associated with developing an IFE demonstration plant;
- Advise the U.S. Department of Energy on its development of an R&D roadmap aimed at creating a conceptual design for an inertial fusion energy demonstration plant.

The Committee will also prepare an interim report to inform FY 2012 budget deliberations. A Panel on Fusion Target Physics will serve as a technical resource to the committee.

Statement of Task—Fusion Target Physics
A Panel on Fusion Target Physics with access to classified information as well as controlled-restricted unclassified information will serve as a technical resource to the Committee on Inertial Confinement Energy Systems and will describe, in a report containing only publicly accessible information, the R&D challenges to providing suitable targets on the basis of parameters established and provided by the Committee. The Panel will also assess the current performance of various fusion target technologies."

In a 2003 letter from Burton Richter (SLAC) to Charles Baker (Chair, FESAC): *"…the vast majority of inertial fusion funding into lasers and pulsed-power while a whole series of review panels, going back to the late 1970's, have consistently indicated that HIF has the most promise as a source of energy … The HIF Program has been consistently starved for funds, … I would further recommend that there be some kind of coordinated review of the NNSA and SC Inertial Fusion Programs. Such a coordinated review would most likely come out with the same conclusion that all previous reviews have come out with, to wit, the HIF Program is the most promising route to civilian energy ..."*

Workshop on Accelerators for Heavy Ion Inertial Fusion
LBNL, March/April (3-4 days), **2011**

There is a growing interest in the development of energy solutions that can provide carbon-free, base-load electricity.

The purpose of the Workshop is to review the status of heavy ion fusion (HIF) research, and to identify the most promising areas of research. We are bringing together experts in these areas:

- **Fusion target physics**
- **Ion sources**
- **Induction accelerators**
- **RF accelerators (including linacs, synchrotrons, storage rings, cyclotrons)**
- **Superconducting magnets**
- **Chamber and chamber - driver interface**
- **Technology development (e.g.: insulators, high-voltage pulsed power, RF systems, vacuum systems)**

Accelerator physicists from a variety of areas of expertise have expressed interest…

Ingo Hofmann	**(GSI, Franfurt U.) High current and intensity beam dynamics**
R. Garnett	**(LANL) – RF and induction accelerators**
G. Sabbi	**(LBNL) superconducting magnet arrays for HIF**
B. Sharkov	**(GSI, FAIR Scientific Director) Heavy ion fusion**

& seeking participation from CERN, FNAL , BNL, SNL…

FAIR will provide intense heavy ion beams that can be used to explore hydrogen compression and heating, and to test new focusing optics using the world's highest energy and intensity heavy ion beams.

Registered office: Darmstadt

We encourage consideration of this opportunity for the benefit of heavy ion fusion research.

Darmstadt, November 11th, 2010

Boris Y. Sharkov
FAIR Scientific Director

Darmstadt, November 11th, 2010

B. Grant Logan

B. Grant Logan
US Heavy Ion Fusion Science
Virtual Natural Laboratory

Extras

DOE symposium: “Accelerators for America’s Future.”

In October 2009, the Department of Energy’s Office of High Energy Physics sponsored a symposium and workshop, “Accelerators for America’s Future.” The charge was to give their perspective on needs, challenges and areas of greatest promise; and to provide guidance on bridging the gap between accelerator research and technology deployment. Five working groups in Energy and Environment, Industry, Medicine, National Security and Discovery Science contributed to the report. **Heavy ion driven inertial fusion energy** was noted as an approach to fusion energy production with particular advantages and promise.

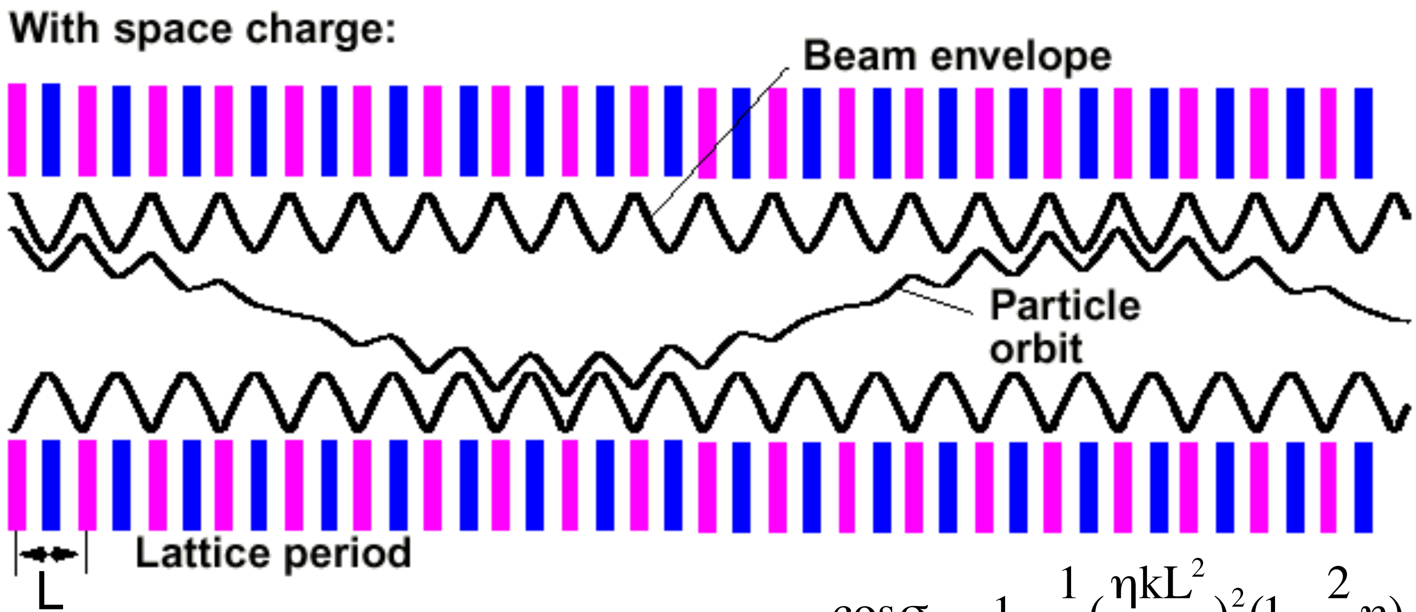
Except at the target, beam is space-charge dominated. Depressed phase advance $\sigma \ll \sigma_o$. $\sigma \approx 0.1$ Unusual!

Transverse envelope

$$\mathbf{a}'' = -\mathbf{k}\mathbf{a} + \frac{\varepsilon^2}{\mathbf{a}^3} + \frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}} \qquad K \equiv \frac{q\lambda}{2\pi\varepsilon_0 mc^2\beta^2\gamma^3} \approx \frac{q\lambda}{4\pi\varepsilon_0 E_{kin}} \qquad k = \frac{qE'}{mv^2}, \quad \frac{qB'}{mv}$$

For HIF,

$$\frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}} >> \frac{\varepsilon^2}{\mathbf{a}^3}$$



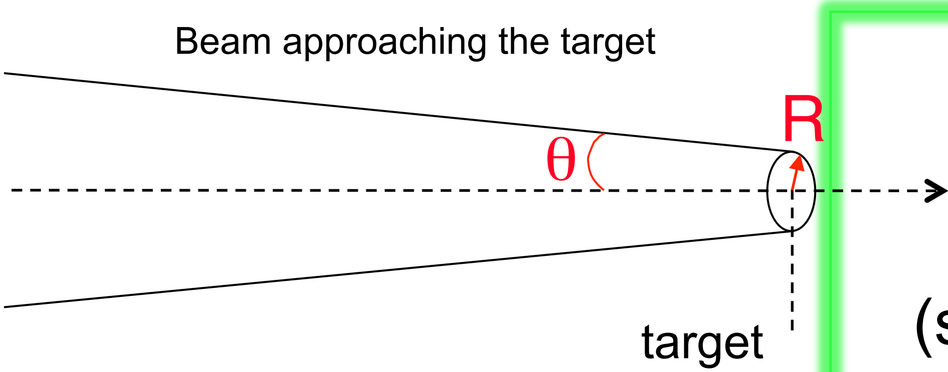
$$\cos\sigma_o = 1 - \frac{1}{2}\left(\frac{\eta k L^2}{4}\right)^2\left(1 - \frac{2}{3}\eta\right)$$

$$K\left(\frac{2L}{2a}\right)^2 = 2(\cos\sigma - \cos\sigma_o)$$

For quadrupoles, $\sigma_o \leq 85^o$

longitudinal occupancy = η

Accelerators are long. What about lower ion kinetic energy? Lower driver energy (MJ)?



Beam phase space density

$$\rho_{6D} \propto \frac{P}{T^3\delta \bullet R^2\theta^2 N_b}$$

$$\delta = \frac{\Delta T}{T}$$ (energy spread)

$$\theta \equiv \text{convergence}$$

Lower kinetic energy

and

lower driver energy

(smaller targets → smaller R)

places greater demands on beam quality. Feasible? Cost?

Optimization problem:
lowest cost HIF system ≠ lowest driver energy, K.E.

Many elements of the Snowmass development plan (Snowmass '02) are still valid and well motivated